Ion Source 101

What you always wanted to know about the SNS ion source but were afraid to ask!

Pre-requisite: Physics 101 or E&M 101 or 5 oz. of common sense

Martin P. Stockli

Ion Source Group Leader

December 4, 2001

Not recommended by the Chef: the Ion Source Buffet

- Bayard-Alpert type ion source
- Electron Bombardment ion source
- Hollow Cathode ion source
- Reflex Discharge Multicusp source
- Cold- & Hot-Cathode PIG
- Electron Cyclotron Resonance ion source (ECR)
- Electron Beam Ion Source (EBIS)
- Surface Contact ion source
- Cryogenic Anode ion source
- Metal Vapor Vacuum Arc ion source (MEVVA)
- Sputtering-type negative ion source
- Plasma Surface Conversion negative ion source
- Electron Heated Vaporization ion source
- Hollow Cathode von Ardenne ion source
- Forrester Porus Plate ion source
- Multipole Confinement ion source
- EHD-driven Liquid ion source
- Surface Ionization ion source
- Charge Exchange ion source
- Inverse Magnetron ion source
- Microwave ion source
- XUV-driven ion source
- Arc Plasma ion source
- Capillary Arc ion source
- Von Ardenne ion source
- Capillaritron ion source
- Canal Ray ion source
- Pulsed Spark ion source
- Field Emission ion source
- Atomic Beam ion source
- Field Ionization ion source
- Arc Discharge ion source
- Multifilament ion source
- RF plasma ion source
- Freeman ion source
- Liquid Metal ion source
- Beam Plasma ion source
- Magnetron ion source
- Nier ion source
- Bernas ion source
- Nielsen ion source
- Wilson ion source
- Recoil ion source
- Zinn ion source
- Duoplasmatron
- Duopigatron
- Laser ion source
- Penning ion source
- Monocusp ion source
- Bucket ion source
- Metal ion source
- Multicusp ion source
- Kaufman ion source
- Flashover ion source
- Calutron ion source
- CHORDIS

- *What is an Ion Source?*
- *How where the Ions discovered?*
- *How are Ions made?*
- *How are more Ions made?*
- *What are the Vacuum Limits of Ion Sources?*
- *What are the Lifetime Limits of Ion Sources?*
- *How are Negative Ions made?*
- *How are more Negative Ions made?*
- *What are the options for the SNS Ion Source?*
- *Summary and Conclusions*

What is an Ion Source?

- **Ion Source** **i·on source** noun

  device for producing ions: *a device that produces a stream of ions, especially for use in particle accelerators or ion implantation equipment.*

- **Ion** **i·on** [ī òn] (plural **i·ons**) noun

  electrically charged atom or atom group: *an atom or group of atoms that has acquired an electric charge by losing or gaining one or more electrons.*

  [Mid-19th century. From Greek ion , literally "moving thing," from the present participle of ienai "to go," from the movement of any ion toward the electrode of opposite charge.]

How where the Ions discovered ? I

From "Physics," Microsoft® Encarta® Online Encyclopedia 2001; http://encarta.msn.com

That electric charges were carried by extremely small particles had already been suspected in the 19th century and, as indicated by electrochemical experiments, the charge of these elementary particles was a definite, invariant quantity.

Experiments on the conduction of electricity through low-pressure gases led to the discovery of two kinds of rays: cathode rays, coming from the negative electrode in a gas discharge tube, and positive or canal rays from the positive electrode.

Sir Joseph John Thomson's 1895 experiment measured the ratio of the charge q to the mass m of the cathode-ray particles.

Lenard in 1899 confirmed that the ratio of q to m for photoelectric particles was identical to that of cathode rays.

The American inventor Thomas Alva Edison had noted in 1883 that very hot wires emit electricity, called thermionic emission (now called the Edison effect), and

in 1899 Thomson showed that this form of electricity also consisted of particles with the same q to m ratio as the others.

How where the Ions discovered ? *II*

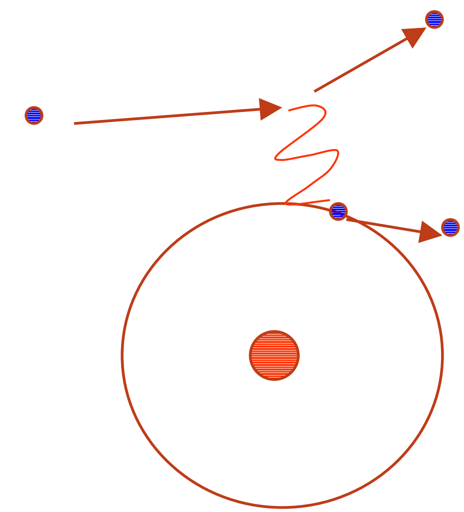
About 1911 Millikan finally determined that electric charge always arises in multiples of a basic unit e, and measured the value of e, now known to be 1.602×10^{-19} coulombs. From the measured value of q to m ratio, with q set equal to e, the mass of the carrier, called electron, could now be determined as 9.110×10^{-31} kg.

*Finally, Thomson and others showed that the positive rays also consisted of particles, each carrying a charge e, but of the positive variety. These particles, however, now recognized as positive ions resulting from the removal of an electron from a neutral atom, are much more massive than the electron. The smallest, the hydrogen ion, is a single proton with a mass of 1.673×10^{-27} kg, about 1837 times more massive than the electron (see Ion; **Ionization**).*

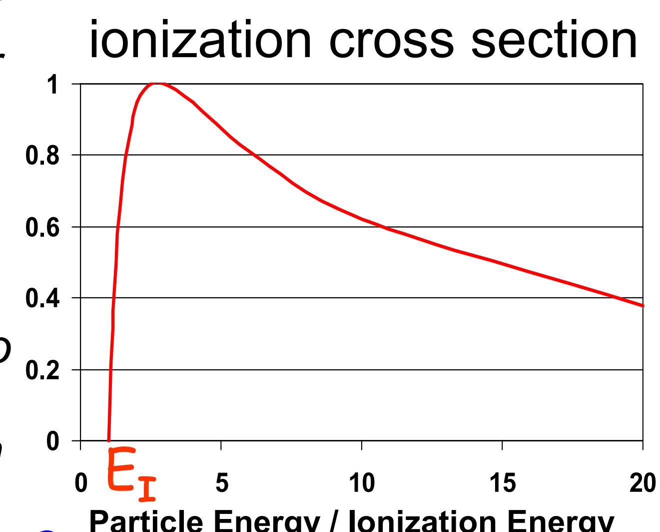
The "quantized" nature of electric charge was now firmly established and, at the same time, two of the fundamental subatomic particles identified.

Ionization of Atoms and Molecules in Gases

- *Ionization in gases, the removal of an electron from an atom or molecule, requires an electric field in excess of 10^{10} V/m, only possible within atomic distances typically reached in collisions with charged particles [$F_C = (4\pi\epsilon_o)^{-1} \cdot q_1 \cdot q_2 / r_{12}^2$].*
- *The conservation of energy and momentum favors electrons as the most efficient ionizing particles, and therefore most ion sources use electron impact ionization.*
- *The conservation of energy is responsible for an absolute threshold, the ionization energy E_I, the minimum energy which needs to be transferred for successful ionization.*



- *Gases have ionization energies between 12.1 eV for O_2 and 24.6 eV for He, e.g. 15.4 eV for H_2 molecules and 13.6 eV for H atoms.*
- *The electron impact ionization cross sections are typically 10^{-16} cm^2, roughly the size of the atoms.*
- *The ionization cross section has a maximum close to 3 times the ionization energy E_I and therefore electrons with an energy between 50 and 100 eV can ionize all gases efficiently.*



How do we produce ionizing electrons?

Thermionic Generation of Free Electrons

- *The core of metal atoms keeps the conduction electrons trapped inside the metal with the potential Φ, the work function. This is the energy required to remove one electron from the metal, normally between 4.5 and 6 eV.*
- *When heated to a temperature T [in ºK] some of the electrons get enough energy to overcome the work function and escape the metallic filament (Thermionic Emission).*
- *Applying sufficient negative (arc) voltage to the filament allows the electrons to be removed with a current density j [$A \cdot m^{-2}$]:* $\boldsymbol{j = A \cdot T^2 \cdot \exp(-e\Phi/kT)}$

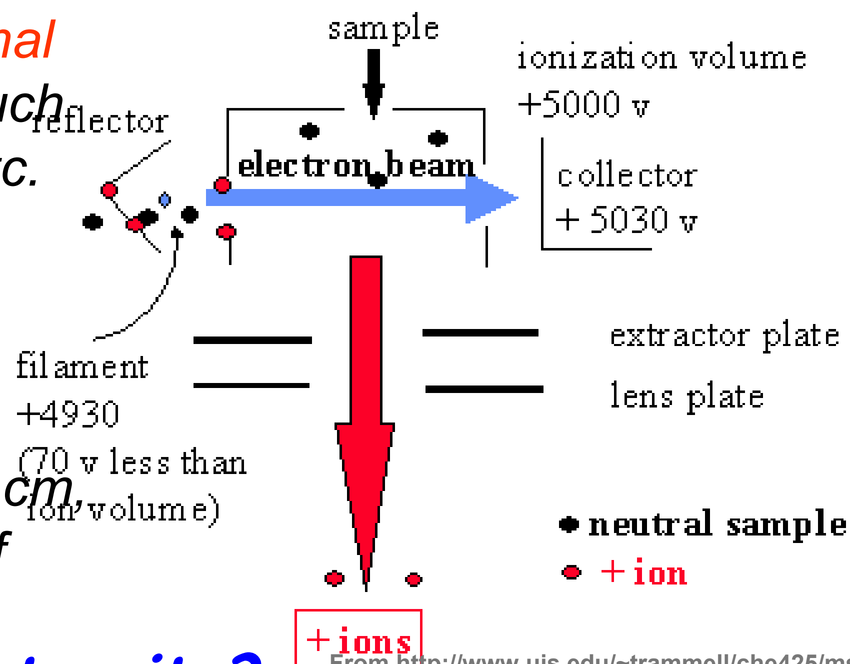
  with $A \sim 600{,}000\ A \cdot m^{-2} \cdot K^{-2}$

- *High currents require high temperature*
- *High currents require large filaments*

The Electron Bombardment Ion Source

- *A simple application of the discussed concepts is the Electron Bombardment Ion Source. Some people call it Electron Impact Ion Source.*
- *This ion source uses thermionic emission from a very hot wire, the filament, to generate an abundance of electrons.*
- *Applying roughly -70 Volts to the filament allows the electrons to gain enough energy to effectively ionize all atoms and molecules.*
- *This ion source is preferred when the ionization rate should be proportional to the gas density, the pressure, such as in gas analyzers, ion gauges, etc.*
- *The filament lifetime is limited by vaporization and sputtering, especially at higher pressures.*
- *At 1 mT pressure, it takes roughly 300 electrons to produce 1 ion per cm, not well suited for the production of high intensity ion beams.*

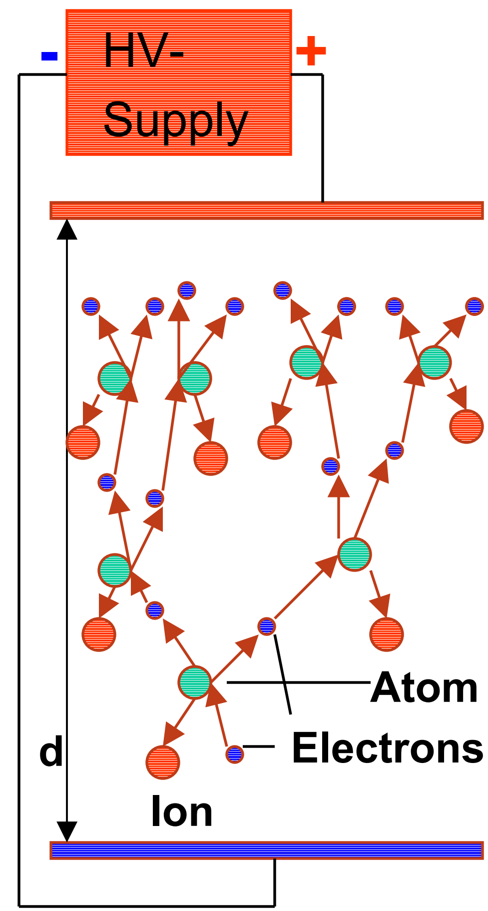
How do we increase the intensity?



From http://www.uis.edu/~trammell/che425/ms-1/

The Electron Multiplicity in Townsend Discharges

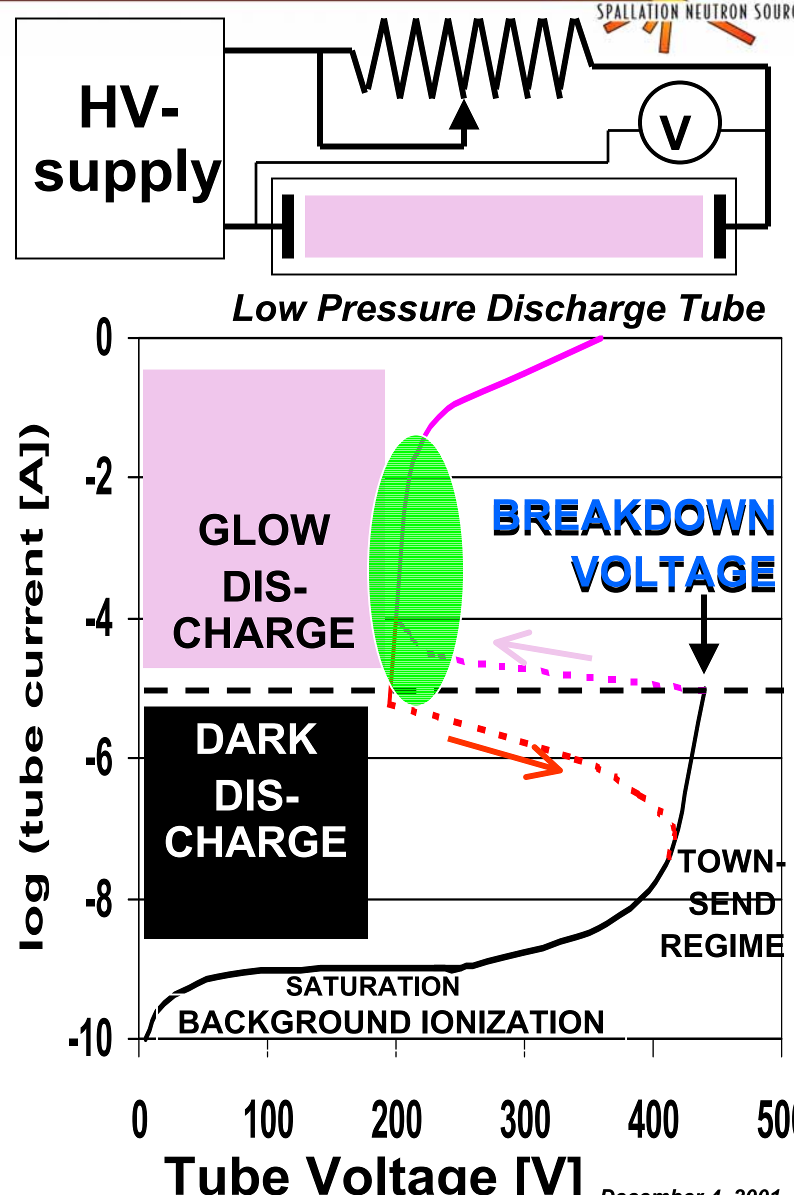
- *Ionization rates can be increased with discharges.*
- *Townsend discharges occur when the electric field and the gas pressure allow free electrons to gain energy in excess of the ionization energy between two subsequent collisions (mean free path for ionization λ_i.*
- *As the ionizing electron and the ionized electron both (re-)gain enough energy and ionize again, they start an avalanche. The resulting discharge current grows exponentially with* d, *the gap between the anode and cathode, if the voltage is increased proportional to d.*
- *Keeping the electrode gap d constant, and varying the pressure, the discharge current will reach a maximum when the average energy cost per ionization is minimum at the Stoletow point: p_{opt}[Torr] = E[V/m] /35,000 for H_2, This means that the minimum average energy cost per ionization is 33 eV for H_2 .*



Exponential growth, that is promising !!

Electrical Discharges in Low Pressure Gases

- *Applying a small voltage to a discharge tube typically results in nA's of current produced by background ionization.*
- *When the voltage is raised significantly the current starts to grow exponentially up to many µA due to Townsend multiplication and the onset of corona.*
- *Further increasing the voltage, suddenly the gas starts to glow and the current grows up to many mA at a much reduced voltage. The glow discharge is maintained and amplified by secondary electrons emitted when the ions impact on the cathode.*
- *As glowing plasma covers a growing fraction of the volume, a growing voltage increase is needed to increase the current.*



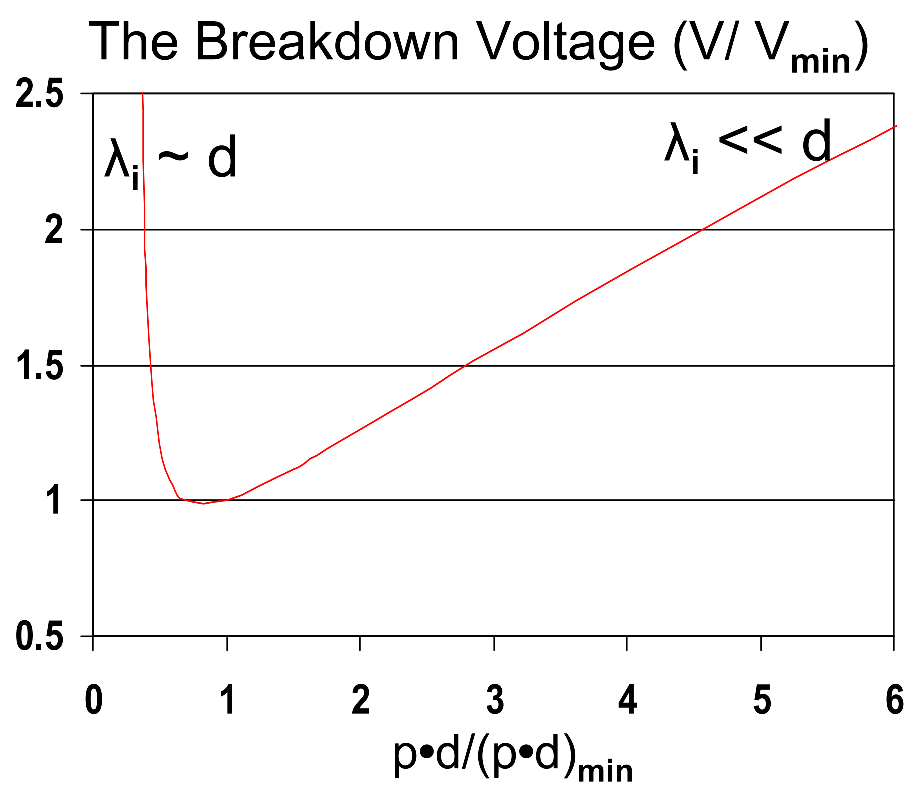
- *Most discharge ion sources operate at the low current end of glow discharges.*

The Breakdown Voltage (Paschen's Law)

- *The voltage at which a low pressure gas breaks down depends only on the ratio of the electrode gap d and the mean free path for ionization λ_i, or p•d, the product of gap d and the pressure p.*
- *The minimum voltage and corresponding p•d depend on the gas and secondary electron emission coefficient of the cathode material.*

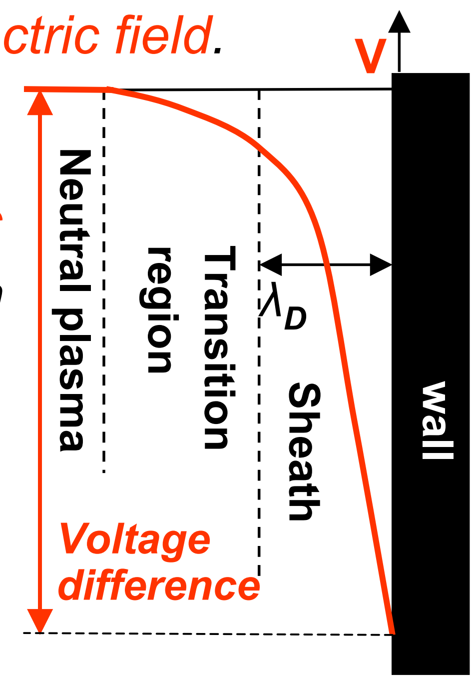
Gas	Cathode	V_{min} (V)	$(p\bullet d)_{min}$ (Torr•mm)
Air		360	15
H_2	Pt	295	12.5
He	Fe	150	25

- *No breakdown occurs at very low pressure and at very high pressure.*
- *Therefore, one normally starts a discharge ion source by first applying the arc voltage and then slowly increasing the gas pressure until a* ***plasma*** *develops.*



The Plasma Physics of Ion Sources

- *A plasma is composed of neutrals, electrons and ions with densities n_n, n_e, and n_i, typically in the range between 10^{10} to 10^{16} particles per cm^3 corresponding to a* **pressure between** *10^{-6} and 0.1 Torr.*
- *The repulsive nature of equal charges requires that essentially all plasmas are practically neutral (quasi-neutral): $e \cdot \Sigma Q_i \cdot n_i = e \cdot n_e$*
- *Plasma physics dominates if degree of ionization $n_i/(n_i+n_n)>0.1$.*
- *The average particle speed is $v_p = (8kT_p/\pi m_P)^{1/2}$ with $T_e \geq T_i > T_n$, which means $v_e \geq 43 \cdot v_i$. The rapidly moving electrons leave behind the ions and their space charge creates a or modifies the existing electric field.*
- *Charges interact with other charges only within a distance λ_D, the Debye length: $\lambda_D^2 = \epsilon_o kT_e/e^2 n_e$ or $\lambda_D\,[cm] = 743\,(T_e[eV]/n_e[p/cm^3])^{1/2}$ (A few µm for the SNS ion source). The surface charges on electrodes create a plasma sheath with a thickness λ_D which maintains most of the potential difference between electrodes.*
- *The plasma frequencies are $f_P^2 = n_p \cdot e^2/(4\pi^2 \epsilon_o m_P)$. The SNS ion source has plasma frequency of ~ 100 GHz for the electrons and ~ 2 GHz for the ions and hence the RF interacts with the individual particles.*



Pressure and Vacuum issues of ion sources

•*The non-ionized, neutral particles with density n_p and mass m randomly collide with each other and the walls. For a wall temperature T (in ºK) the average particle velocity is $v_p = (8kT_p/\pi m_p)^{1/2}$, with H_2 at 1.1 miles/s being about 4-times faster than N_2.*

•*Ion sources need an opening to extract the low-energy ions. The SNS ion source has a 7 mm diameter, circular extraction aperture with a 0.38 cm^2 area. Through this area A, neutral particles escape at a rate of $Q = \frac{1}{4} v_p n_p A$, which is about 10^{19}pps from the SNS ion source, or* ***about 1,000 neutrals for each extracted ion.*** *The pressure is maintained by adding about 1 Torr•ℓ/s Hydrogen gas.*

•*The particles have to be removed from the LEBT to limit ion beam charge exchange losses to ~10%. Three pumps, each with a speed S_p of 1500 l/s, keep the LEBT pressure P_L below 10^{-4} Torr ($P_L = Q/S_p$).*

•*Most ion sources have discharge gaps of a few mm, featuring the highest discharge current at a few Torr. The highest extracted ion currents, however, are found at substantially lower pressures. The SNS ion source operates at 20-30 mTorr, 0.003 % standard atmospheres, a particle density n_p of $10^{15}cm^{-3}$.*

The Canal Ray Ion Source

•*A simple application of the discussed concepts is the canal ray ion source. It was invented in the mid-19th century and led to the discovery of the anode rays, which are positive ions.*

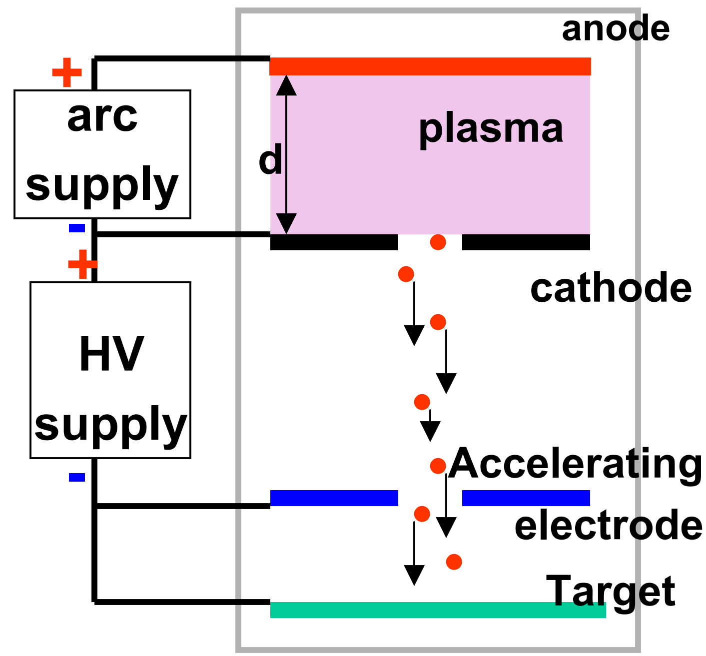
•*When the arc voltage is increased and the gas breaks down, the discharge current jumps to many mA.*

•*However, only a small fraction of the ions sense the electric extraction field penetrating from the accelerating electrode and hence become a part of the ion beam.*

•*A further increase of the arc current increases the fraction of the volume dominated by the plasma further reducing the guiding electric fields.*

•*Without the guiding electric field, the ions and electron are no longer **confine**d, and many hit the walls where they recombine and are lost.*

Canal Ray Ion Source



glass envelope

The canal ray ion source is not suited for producing intense ion beams.

Confinement of Charged Particles

Time-constant magnetic fields are unaffected by plasmas and therefore are perfectly suited to confine ions and electrons.

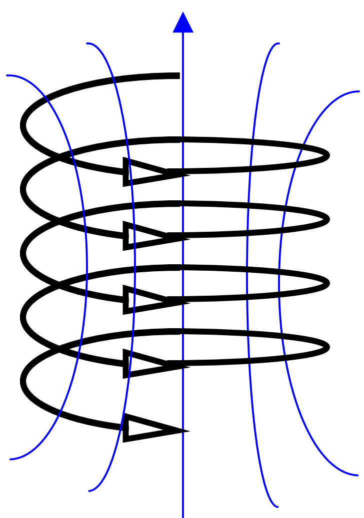
Charged particles move unimpeded in the direction of the magnetic field.

A particle with mass m, charge q, and a velocity v perpendicular to the magnetic field B undergoes a circular motion with a radius $r = mv/qB$.

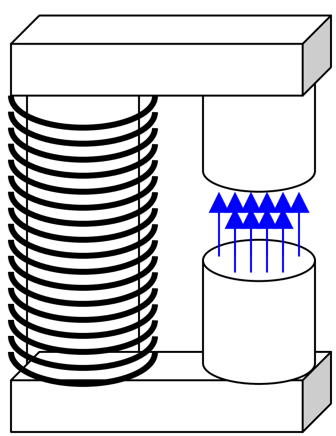
e.g: if B=1 kG, for 10 eV electrons r=0.1mm, for 1 eV protons r = 1.4mm.

The resulting helical particle motion reduces the wall losses of the ions and increases the path length of the electrons and their ionization rate.

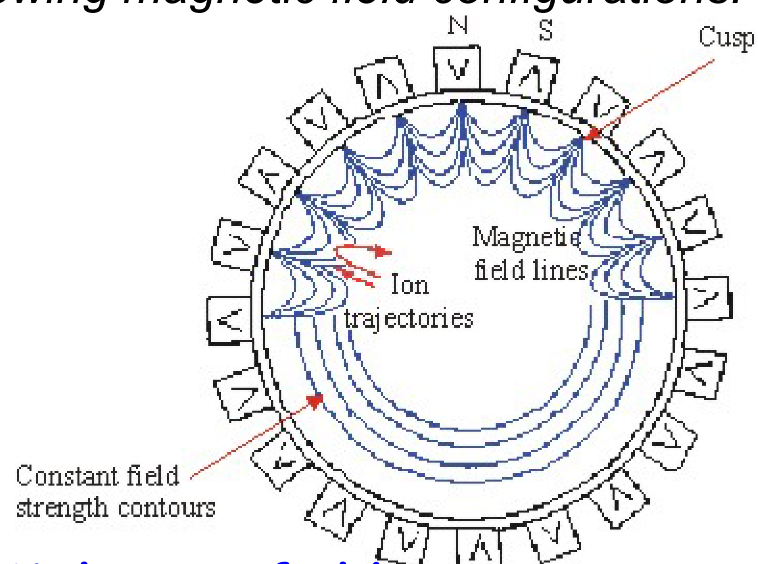
Confinement is normally achieved with the following magnetic field configurations:



Solenoidal field



Dipole field



Multicusp field

The Magnetron Ion Source

A simple application of a solenoidal field for plasma confinement is the Magnetron ion source which was first presented by Van Voorhis in 1934.

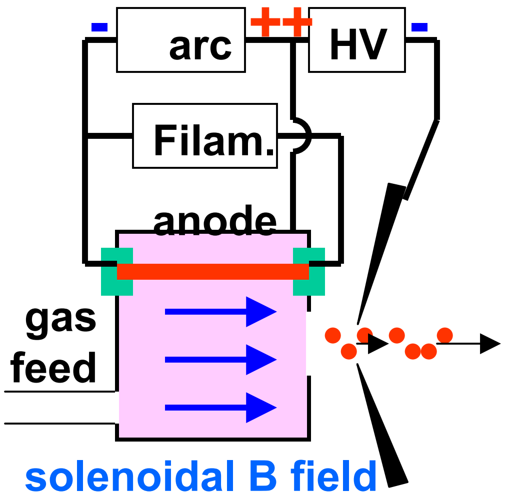
The solenoidal field of ~ 0.1 T is generated with an external solenoid surrounding the ion source.

The chamber wall serves as anode, while the cathode is a heavy duty filament providing electrons through thermionic emission.

The filament mounted parallel to the magnetic field forces the electrons to spiral.

Filament lifetime limited by **sputtering**, especially for heavy gases and/or at higher pressures.

Tends to develop plasma oscillations in the high magnetic field, causing noisy beams.



The Penning Ion Source or PIG source

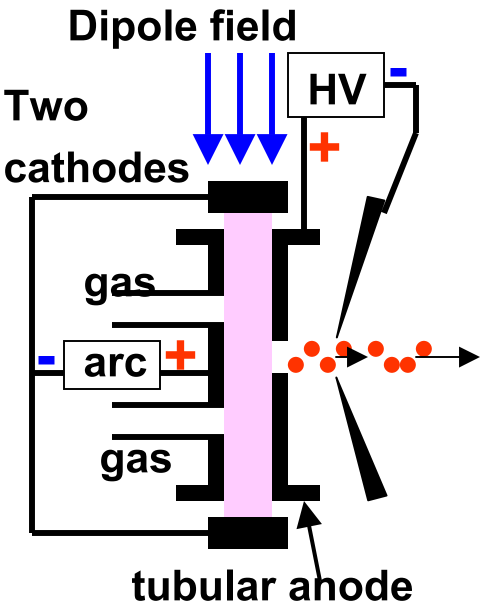
A simple example of application of a dipole field for plasma confinement is the Penning Ion Source or PIG source (Philips Ionization vacuum Gauge) invented by Penning in 1937.

Strong magnetic dipole field gives high efficiency as electrons oscillate inside the hollow anode between the the two cathodes at each end.

Ideal for ion production in existing strong magnetic fields, e.g. internal source for cyclotrons.

*Lifetime limited by **sputtering** of the cathodes, especially for highly charged, heavy ion operation.*

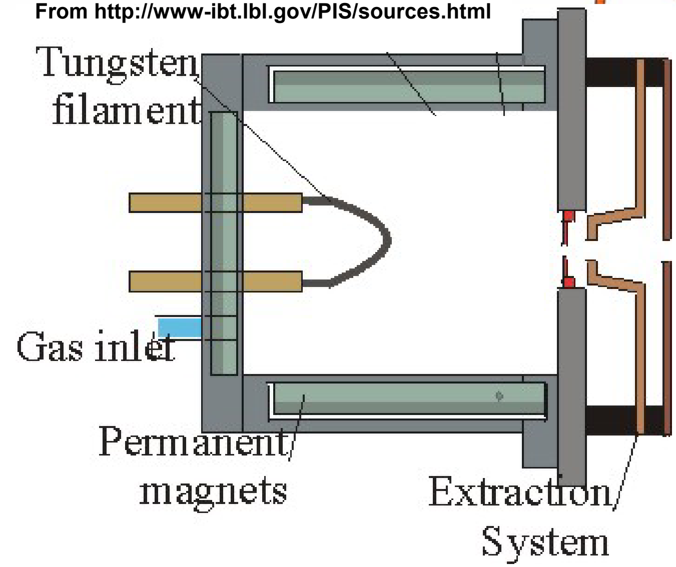
The ion beams tend to be noisy, of medium quality, which changes during operation.

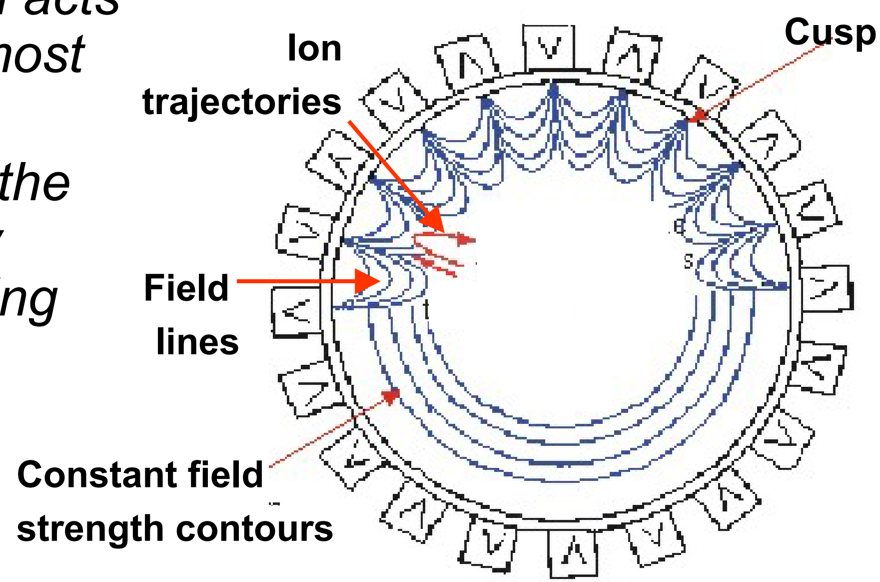


The **Multicusp Ion Source** or **Bucket Ion source**

- *The multicusp ion source was developed at UCLA for fusion in the early 1980s.*
- *The multicusp field is generated by strong permanent magnets (Sm-Co, Nd-Fe, or NdFeB) mounted very close to the vacuum.*
- *The magnetic field decreases with the distance from the wall, and is zero on the axis,a minimum field configuration.*
- *The strong magnetic field at the wall acts as a magnetic mirror which returns most ions back to the center.*
- *The discharge is typically driven by the thermionic emission from heavy duty filament(s) with the chamber wall being the anode.*
- *Filament lifetime limited by **sputtering**, especially for heavy gases and/or at higher pressures.*

From http://www-ibt.lbl.gov/PIS/sources.html





Sputtering, the silent ion source killer !!

•An electric field is required to accelerate the electrons to an energy sufficient to ionize the neutral particles.

•The electric field, however, also accelerates the ions in the plasma sheath at the cathode. These accelerated ions impact on the electrode and sputter atoms away from the electrode.

•Life time extensions are possible with the low sputter rate of heavy, refractory metals:

Material	Sputter Rate @ 1 keV (atoms/ion)	Sputter Threshold (eV)
Cu	0.04	57
W	0.0003	439
Ta	0.0002	740

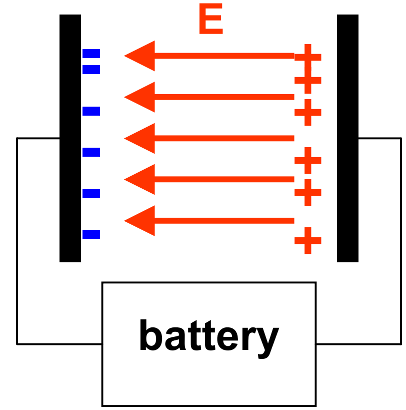
•Sputtering reduces the filament thickness until it breaks.

•Sputtered metal atoms coat insulators until they break down.

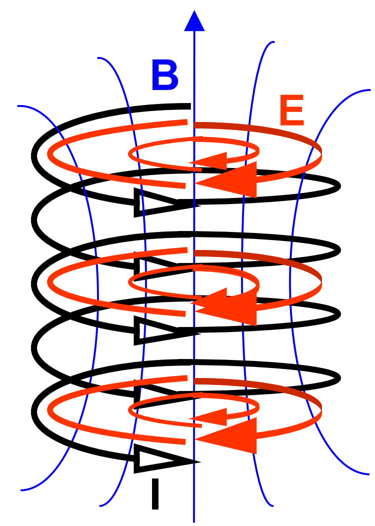
•Insulator lifetimes can be extended with recessed areas providing partial shadow. This extends the lifetime until metal film flakes peeling away from non-shadowed areas short out insulators.

Sputtering limits the lifetime and hence **needs to be minimized!!**

What did Maxwell tell us about Electric Fields ?



- *The 1st Maxwell Equation: $\nabla \cdot E = \rho/\epsilon_o$ states that electric fields are generated by any free net charges and the easy controllable surface charges ρ on electrodes. This explains the need for the surface charges to generate the required electric field. As the negative surface charges attract positive ions the sputtering problem appears unavoidable.*
- *The 2nd Maxwell Equation, however, $\nabla \times E = -\partial B/\partial t$ describes a curling E field generated by a changing magnetic field in absence of any charge!*



A changing magnetic field B can be produced with an alternating current $i = i_o \cdot \cos(\omega t)$ in N windings with radius r_o: $B = \frac{1}{2} \cdot \mu_o \cdot N \cdot i/r_o$ (Biot-Savart).

Now integrate Maxwell's 2nd equation for Faraday's law: $\int \mathbf{E} \cdot d\mathbf{s} = -d\Phi_B/dt = -d/dt \int \mathbf{B} \cdot d\mathbf{A}$

and solve for E: $E(r,t) = \frac{1}{4} \cdot r/r_o \cdot \mu_o \omega N \cdot i_o \cdot \sin(\omega t)$

This is a circular electric field that bites its own tail rather than a poor electrode!

O.K. But does it work??

Inductive-coupled plasma in the SNS test dome

This photo shows an inductive coupled plasma generated with 13 MHz RF being applied to the SNS-style, 2½ turn antenna mounted in our test dome. The test dome has the same size and the same electrical and magnetic boundary conditions as the plasma chamber of the SNS ion source. The test dome allows one to observe the plasma but not to extract ions.

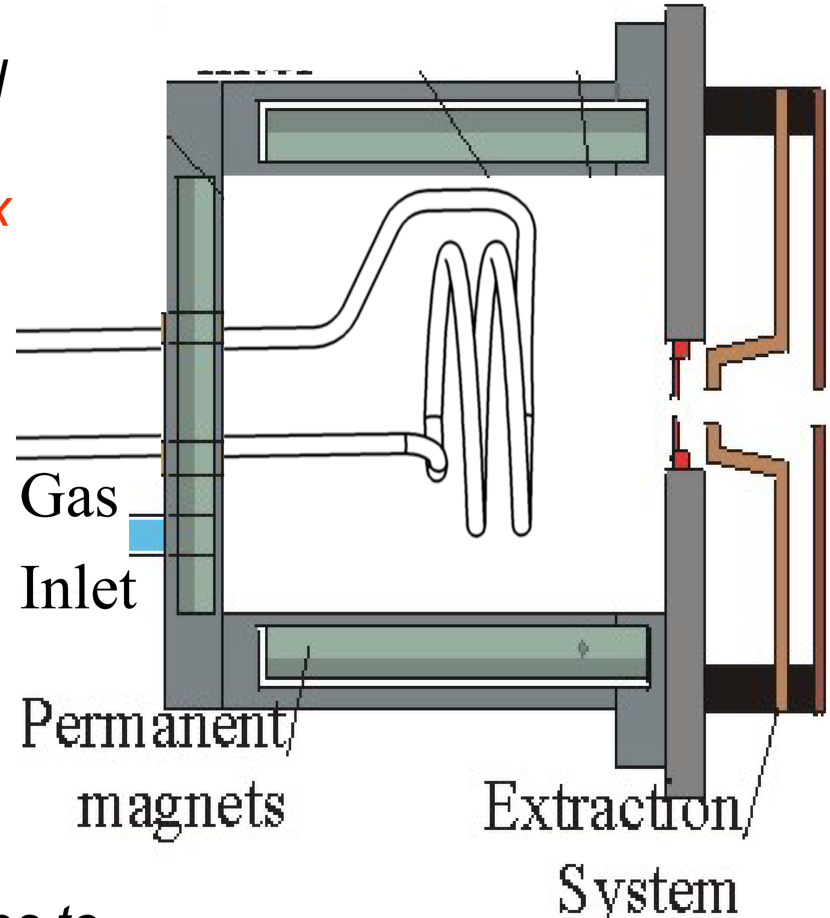
The curling E-field is concentrated inside the solenoidal antenna loops with the highest ionizing field close to the antenna. This is well suited for producing plasma in a large volume which can easily be confined with a multicusp magnetic field.

***Sputtering is** practically **eliminated** because the curling E-field accelerates the ions in azimuthal direction !!*

How about the ion output ?

The RF driven multicusp ion source

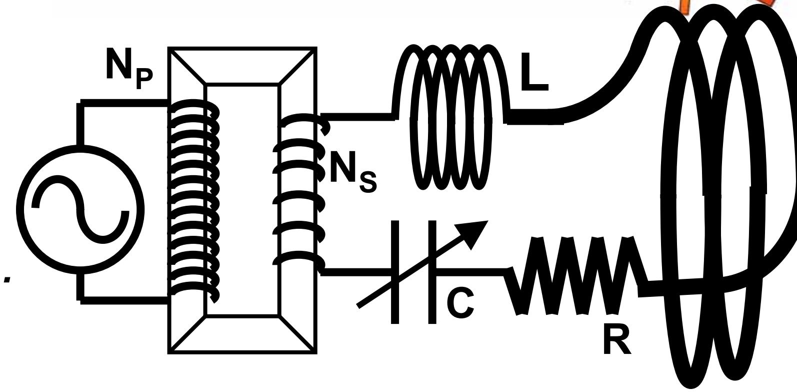
- The multicusp minimum field configuration as well as the solenoidal field generated in an RF-driven multicusp ion source favors an ion flux towards the extraction aperture.
- In 1994 this ion source has been selected for SNS due to the favorable experience with the SSC ion source as well as due to the expected long lifetime and expected quiet plasma.
- The peak electric field $E(r) = ¼•r/r_o•\mu_o\omega N•i_o$ is proportional to the antenna current i_o.
- Increasing the ion output requires to increase the ion density, which requires to increase the ionization rates, which requires to increase the electric fields, which requires to increase the antenna current.



How do we increase the antenna current?

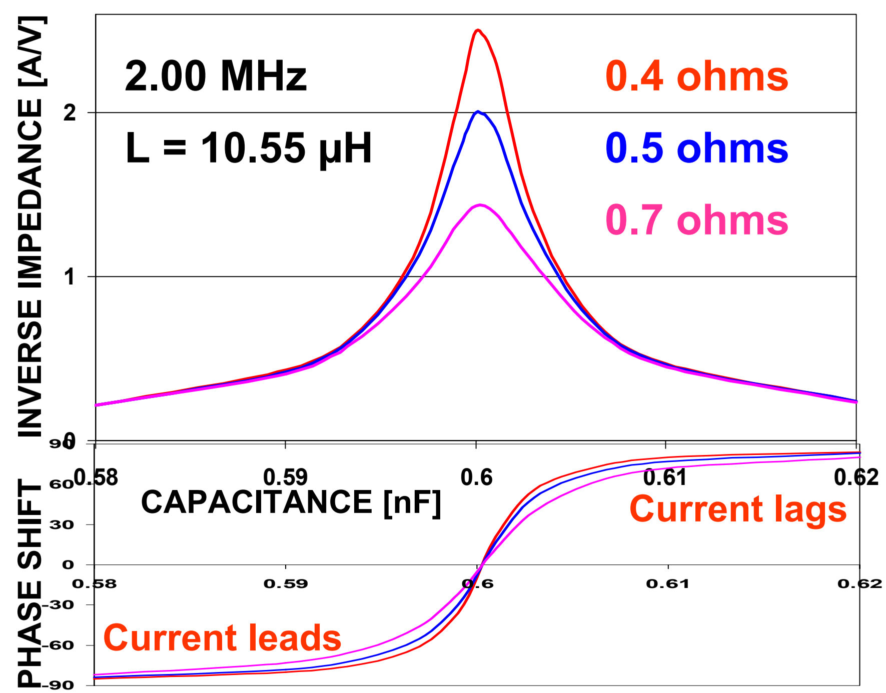
Matching an RF driven ion source

- *To increase the antenna current we need to match the RF amplifier output impedance with the impedance of the antenna circuit and to tune the antenna/plasma system to its resonance.*



- *The output impedance of the RF amplifier is matched to the antenna network impedance by adjusting the transformer ratio N_S/N_P.*
  - *The antenna/plasma RLC circuit has a resonant frequency of $\omega^2 = (LC)^{-1}$ and an impedance $Z = \mathcal{E}_o/i_o = (R^2+(\omega L-(\omega C)^{-1})^2)^{1/2}$*
  - *With $L \approx 10$ μH and $\omega \approx 2 \cdot \pi \cdot 2$ MHz we need to tune C around 0.6 nF until we obtain the maximum current $i_o = \mathcal{E}_o/R$.*
  - *If needed the resonance can be located with the phase shift.*

ANTENNA CURRENT versus CAPACITANCE

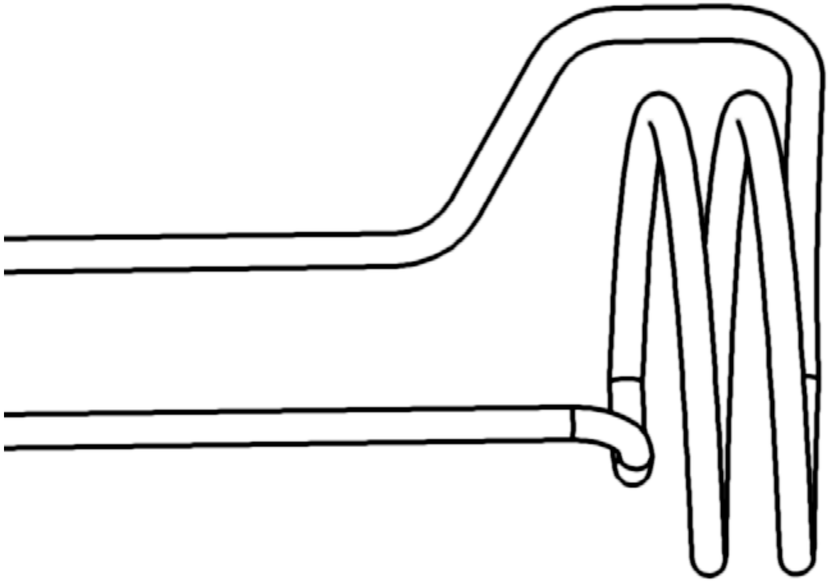


The **self-induced Voltage** in Rf antennas

- *The antenna is a coil with N turns of radius r_o. The ratio between the total enclosed magnetic flux Φ_B and the current is the definition of the inductance $L = \Phi_B/i = N \cdot B \cdot \pi \cdot r_o^2/i = ½ \cdot \pi \cdot \mu_o \cdot r_o \cdot N^2$*

For $r_o = 33$ mm, $N=2½$:

$L = 0.4\ \mu$Henry



The induced voltage is $\epsilon_L = - L \cdot di/dt = \omega \cdot L \cdot i_o \sin(\omega t)$.

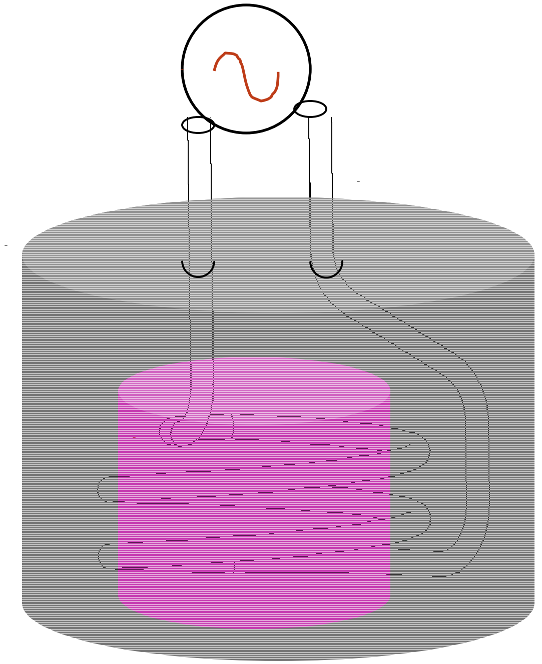
For 2 MHz: $\epsilon_L = 5 \cdot i_o[A] \cdot \sin(\omega t)$

The induced voltage becomes significant as we crank up the RF power to increase the ion current output, e.g. 1.2 kV peak with 240 A when delivering 34 kW RF power.

So what happens when we crank up the RF power?

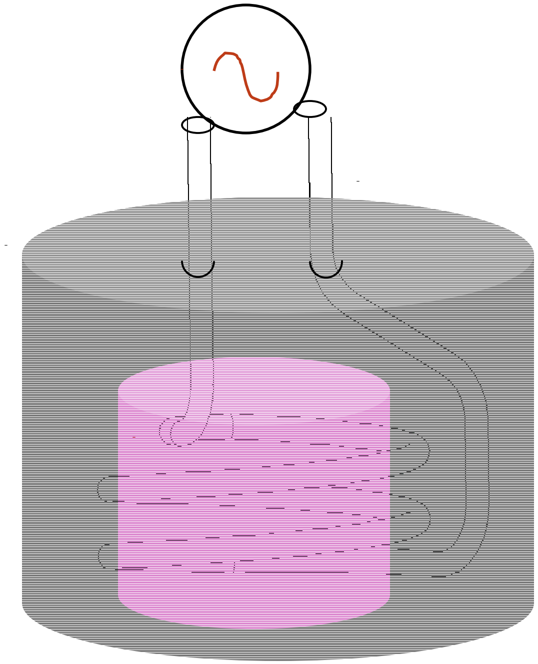
Cranking up the RF Power

- *LBNL (J. Reijonen, RSI 71(2000)1134) and Chiang Mai University (D. Boonyawan, priv. comm. 2000) observe practically infinite antenna lifetime when operating at low RF power.*



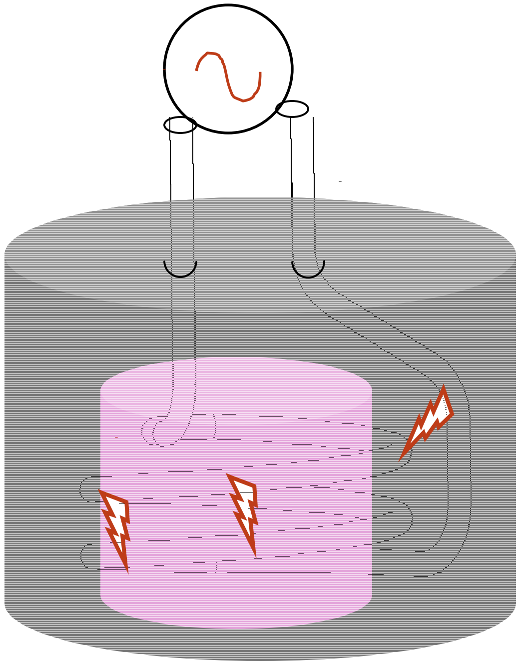
Cranking up the RF Power

- *LBNL (J. Reijonen, RSI 71(2000)1134) and Chiang Mai University (D. Boonyawan, priv. comm. 2000) observe practically infinite antenna lifetime when operating at low RF power.*
- *Increasing the RF power increases the antenna current and the induced voltage. The increased power increases the plasma density, but decreases the plasma impedance.*



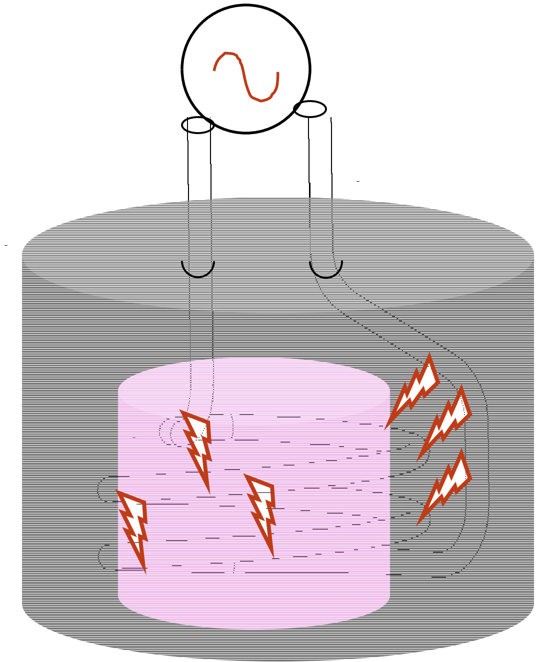
Cranking up the RF Power

- LBNL (J. Reijonen, RSI 71(2000)1134) and Chiang Mai University (D. Boonyawan, priv. comm. 2000) observe practically infinite antenna lifetime when operating at low RF power.
- Increasing the RF power increases the antenna current and the induced voltage. The increased power increases the plasma density, but decreases the plasma impedance.
- As the induced antenna voltage increases and the plasma impedance decreases more and more RF current bypasses the antenna coils through the plasma. This slowly changes the inductive coupled plasma to a capacitive coupled plasma, changing the resonance condition.



Cranking up the RF Power

- LBNL (J. Reijonen, RSI 71(2000)1134) and Chiang Mai University (D. Boonyawan, priv. comm. 2000) observe practically infinite antenna lifetime when operating at low RF power.
- Increasing the RF power increases the antenna current and the induced voltage. The increased power increases the plasma density, but decreases the plasma impedance.
- As the induced antenna voltage increases and the plasma impedance decreases more and more RF current bypasses the antenna coils through the plasma. This slowly changes the inductive coupled plasma to a capacitive coupled plasma, changing the resonance condition.
- As an increasing fraction of the RF current flows through the edge of the plasma, the central plasma density and the resulting ion current output stagnate while the power reflected from antenna/plasma system increases until the RF-amplifier shuts down.



High power operations require an adequate Antenna insulation.

Antenna Lifetimes reported for RF Volume Sources

Lab	Antenna / Coating	MHz Frequency	kW RF-Power	% Duty Cycle	hours Life-time	Reference
Northrop Grumman	Cu tube/ Porcelain SS / bare	2	3.6	100	>260	S.T. Melnychuk, RSI 67(1996)1317.
LBNL	Cu tube / P&G Porcelain Cu braid / Quartz	13.56 13.56	2 2	100 100	~15 ~20	D. Wutte, AIP-CP# 473 (1999) 566.
LBNL	Cu tube / P&G Porcelain Ag wire / Quartz Ti tube / Quartz	13.56 13.56 13.56	2 2 2	100 100 100	< 50 >100 >500	K.N. Leung, RSI 71(2000)1064. J. Reijonen, RSI 71(2000)1134.
DESY	Cu tube / P&G Porcelain	2	45	0.02	984	J. Peters, RSI 71 (2000) 1069
PSI	Cu tube / P&G Porcelain Cu tube / Zug Porcelain Cu tube / blue Porcelain best / Quartz	2 2 2 2	6-8 6-8 6-8 6-8	100 100 100 100	~50 ~100 ~200 ~250	H. Einenkel, private communications 2001.
Chiang Mai U.	Cu braid / Quartz	13.56	0.3	100	>>200	D. Boonyawan, priv. comm.2001

The desired properties of an ideal Antenna Coating

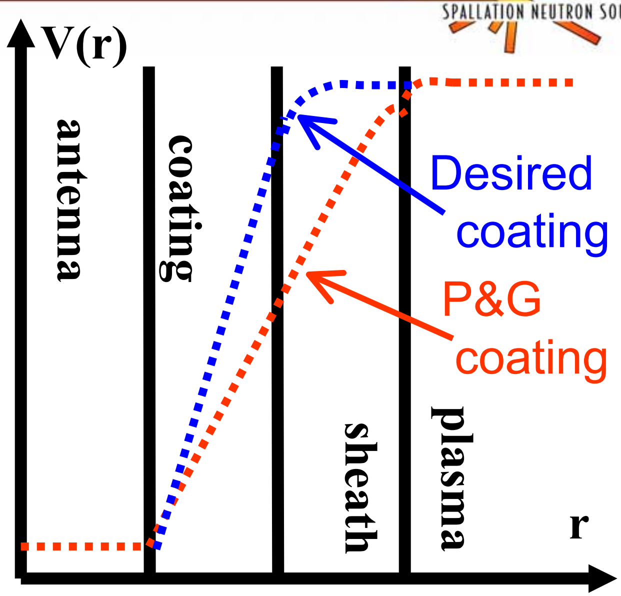
•At high RF power parts of the antenna reach high voltages, which have to be maintained by the coating and the plasma sheath.

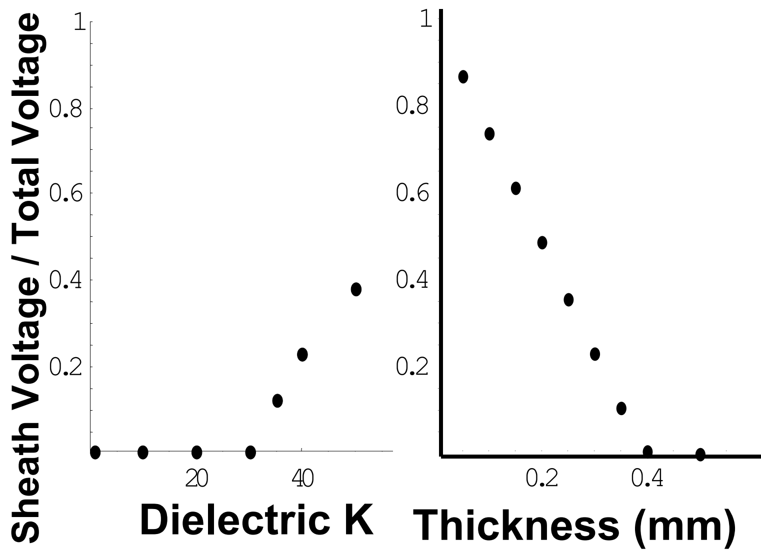
•A relatively low plasma sheath potential difference is desirable to reduce the sputtering of the antenna coating by the ions from the plasma. A numeric electric model was developed to determine the voltage drop over the sheath compared to the total voltage drop. For porcelain ($10^{12}\Omega\bullet m$) the results show that the plasma sheath voltage can practically be eliminated if

•the thickness is 1mm and the dielectric constant K is less than 30 or if

•K is 12 and the thickness is 0.4 mm or more.

Low-dielectric, thick coatings are needed.





Here comes the Cherokee Antenna

- *The dielectric constant of porcelain can be reduced by omitting the TiO_2.*
- *The effect of local defects can be reduced by applying multiple layers because the probability that the defects occur at the same location is small.*
- *Applying multiple layers can also be used to build up thickness.*
- *Cherokee Porcelain Enamel Corporation has coated many antennas with a double layer of Porcelain yielding a 0.3 mm coating.*
- *In addition Cherokee Porcelain coated a few antennas with 10 layers of TiO_2-free Porcelain yielding a 0.7 to 1 mm thick coating.*

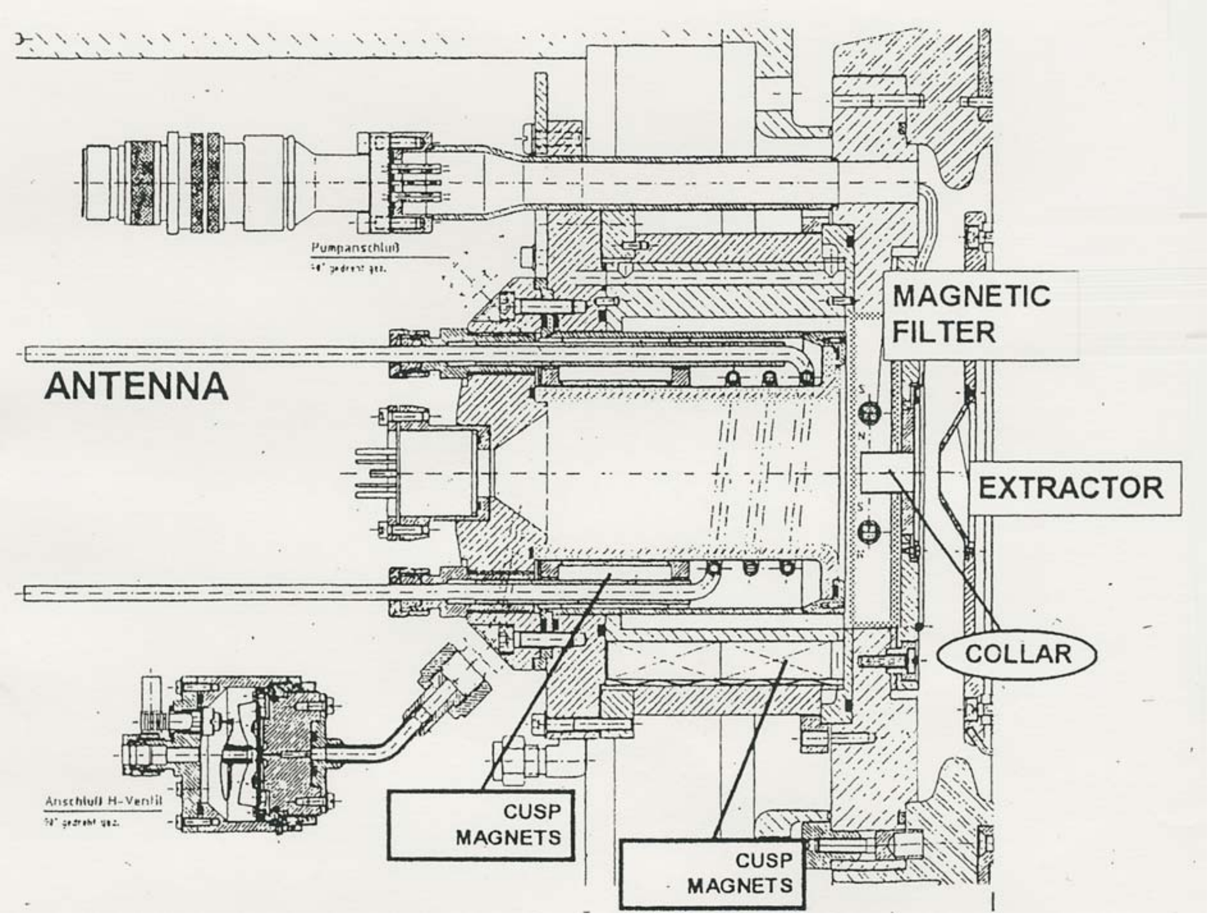
Antenna coated with a double-layer Cherokee Porcelain

So far the Cherokee antennas have essentially passed all the tests with RF power levels up to 33 kW.

Another excellent solution: the DESY air coil

- One can also remove the antenna coil from the discharge-favoring plasma chamber and mount it in air where insulation at the kV level is no problem.
- DESY has developed this ion source with the antenna in ambient air separated from the plasma chamber with with a ceramic tube. So far it has operated for 7000 hours delivering 40 mA of H^- for 0.1 ms with 5 Hz without a sign of degradation!!

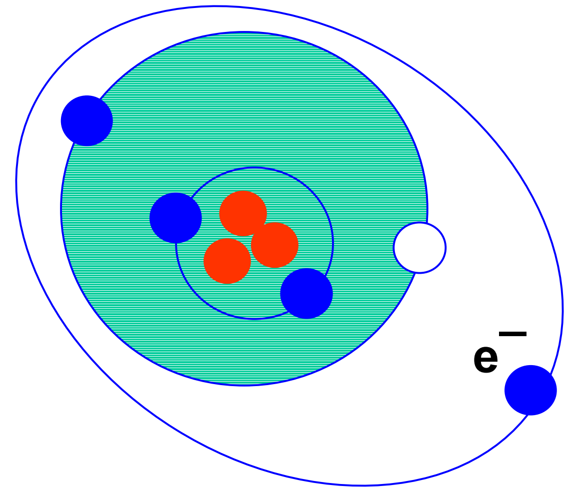
From J. Peters, Rev Sci. Instrum. 71 (2000) 1069



Wait a minute, what is H^-??

Negative Ions; What is that?

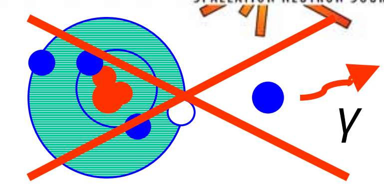
- *Some atoms with an open shell can attract an extra electron and form a stable ion with a net charge of –e.*
- *The stability is quantified by the electron affinity, the minimum energy required to remove the extra electron.*
- *The electron affinities are substantially smaller than the ionization energies, covering the range between 0.08 eV for Ti^- and 3.6 eV for Cl^-, e.g. 0.75 eV for H^-.*
- *For electron energies above 10 eV, the H^- ionization cross section is ~ $30 \cdot 10^{-16}$ cm²,* *30 times larger than for a typical neutral atom!!*
- *For H^+ energies below 1 keV, the recombination cross section is larger than $100 \cdot 10^{-16}$ cm².*
- *Charged particle collisions destroy H^- ions easily!!*



H^- ions are fragile !

How are Negative Ions born?

•Conserving energy when forming a negative ion through *direct electron attachment,* the excess energy has to be dissipated through a photon. $A + e = A^- + \gamma$

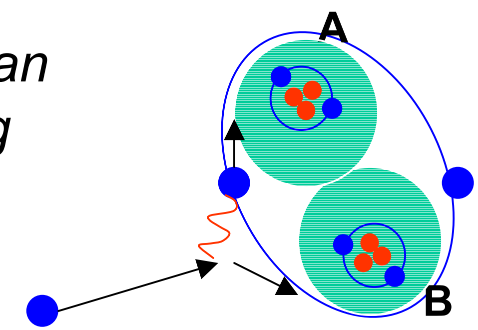


But *Radiative Capture* is *rare* ($5 \cdot 10^{-22} cm^2$ for H_2).

•More likely are processes where the *excess energy* can be *transferred to a third particle,* e.g. when dissociating a molecule (4.5 eV for H_2): $M + e = A + B + e$

and sometimes $= A + B^-$

($\sim 10^{-20} cm^2$ for H_2 and $E_e > 10$ eV)

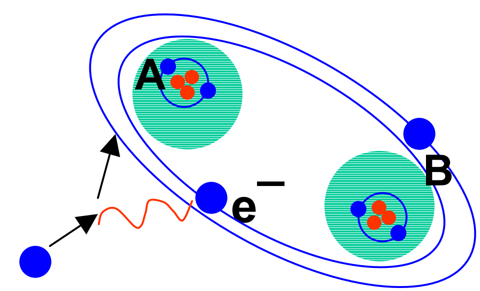


•Most likely are processes which excite a *molecule* to the edge of breakup (*vibrationally excited* $4<n<12$)

$$M + e(fast) = M^* + e$$

and then *dissociated by a slow electron*

$$M^* + e(slow) = A + B^-$$



But the *frequency of 2-step processes is limited!*

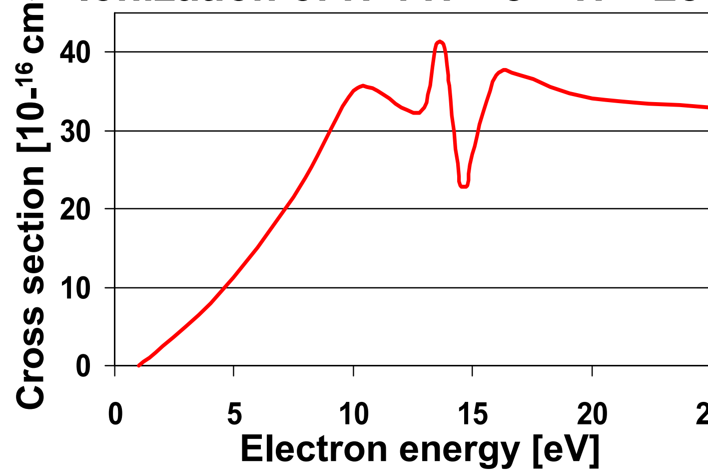
The *small electron affinity* causes the *production* of negative ions to be *unlikely*, but their *destruction* to be *likely* !!

H^-, a rare specie!

Optimizing H⁻ production: *a catch 22*

Hot electrons are required to

- *produce more electrons through ionization of H_2 (E_e > 15.4 eV)*
  produce more electrons through ionization of H (E_e > 13.6 eV)
- *to dissociate H_2 molecules (E_e>4.5 eV)*
- *to excite H_2 molecules*



Unfortunately hot electrons destroy H⁻ ions. On the other hand cold electrons are much less likely to destroy the H⁻ ions.

In addition cold electrons

•produce H⁻ through dissociative recombination of H_2^+.

•produce H⁻ through dissociative attachment of excited molecules.

Can we first have hot electrons to favor ionization and then cold electrons to favor H⁻ production ?

The Seminar Poem

The H⁻ are fools,
when they have hot electrons
they want them cool,
when they have cool electrons
they want them hot,
they never like what they got!

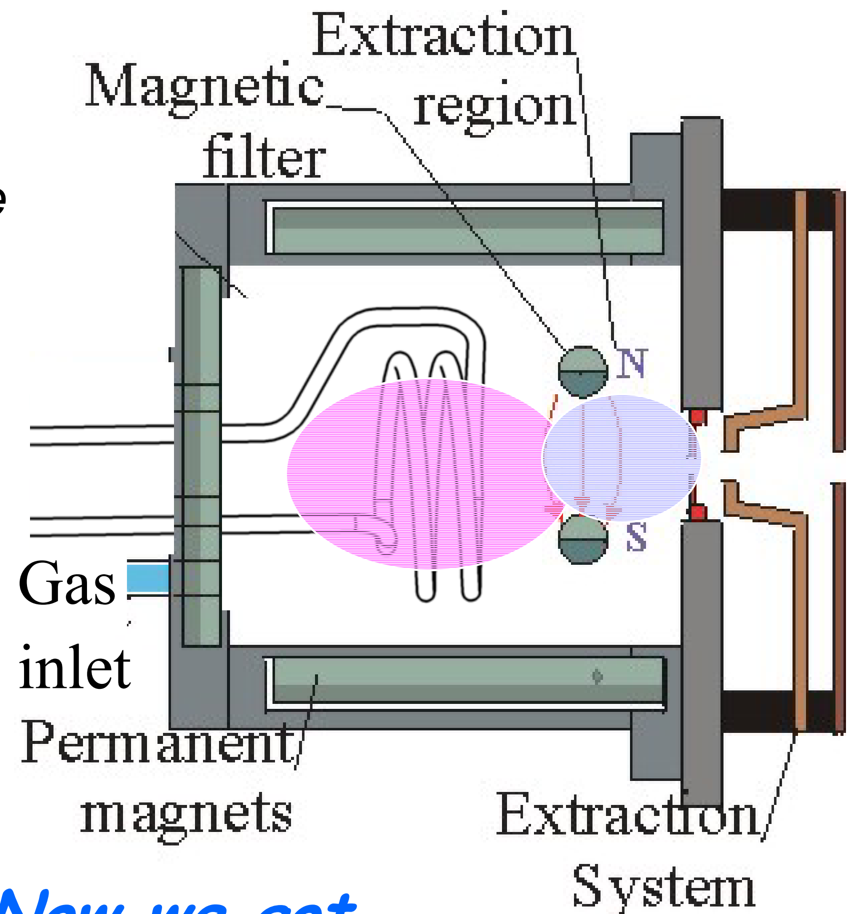
Multicusp Source for negative ions

•*Installing a dipole filter magnet of a few hundred Gauss changes the parameters of the plasma in the extraction region:*

•*The main plasma driven by the RF field generates hot electrons which efficiently excite and ionize atoms and molecules. This hot electrons are reflected by the filter field, e.g. in a 200 Gauss field a 25 eV electron turns around on a 0.03 mm radius.*

•*Cold electrons and cold ions undergo many, many collisions with other cold charged particles, resulting in a diffusion process which favors the cold charged particles (~$T^{-½}$) and therefore the electron temperature decreases exponentially through the filter- and extraction region.*

•*Exited neutral molecules migrate freely to the extraction region.*



Now we got the best of both worlds!!

PS-100 Duoplasmatron Ion Source by Peabody Scientific

- High Currents
- Low Energy Spread
- Positive/Negative Ion Operation
- Low Maintenance

- **Specifications**
  Positive Operation

Total hydrogen beam	1 mA
H1+	> 60%
H2 +	< 20%
H3 +	< 20%
Anode aperture diameter	.25 mm
Gas consumption	10 atm cc/hr
Energy spread	20 eV
Emittance	2 cm rad eV½
Filament lifetime	100's of hours
Other ions include	He, N, C, O, Ar, Kr, I

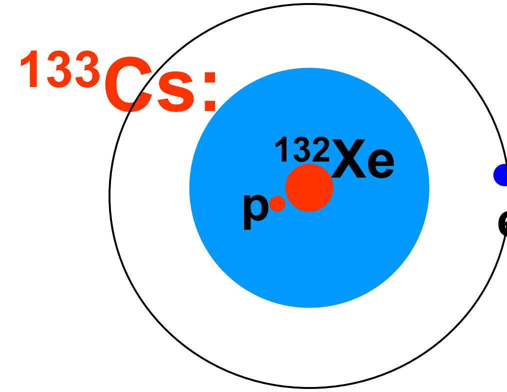
- **Negative Operation**
  To operate the source in a negative ion mode, it is necessary to offset the intermediate electrode from the anode aperture. This results in the extraction of ions from the periphery of the arc discharge which is rich in negative ions with a simultaneous reduction in electrons due to differences in diffusion and recombination coefficients.

H-	150 microamp
Anode aperture diameter	.6 mm
Intermediate electrode offset	1 mm
Emittance	.6 cm rad eV½

How can we make more negative ions?

Cesium, the Negative Ion Booster

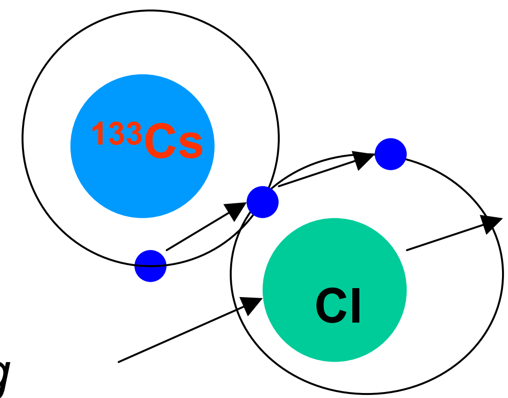
- Cesium has 55 protons, ~78 neutrons, and 55 electrons.
  - This is like the noble ^{132}Xe plus 1 proton plus 1 electron and therefore the last electron is very loosely bound with only 3.9 eV ionization energy. Cs is easily ionized.



The Seminar Joke:

Two Cesium atoms are walking down the street. Says the first Cesium atom, "oh my god! I think I'm missing an electron". Says the second, "are you sure?" Says the first, "I'm positive".

- The ionization energy of Cs is a close match to the 3.6 eV electron affinity of Cl^-. Therefore the outer Cs electron can easily be captured by Cl atoms, boosting the production of negative Chlorine ions.

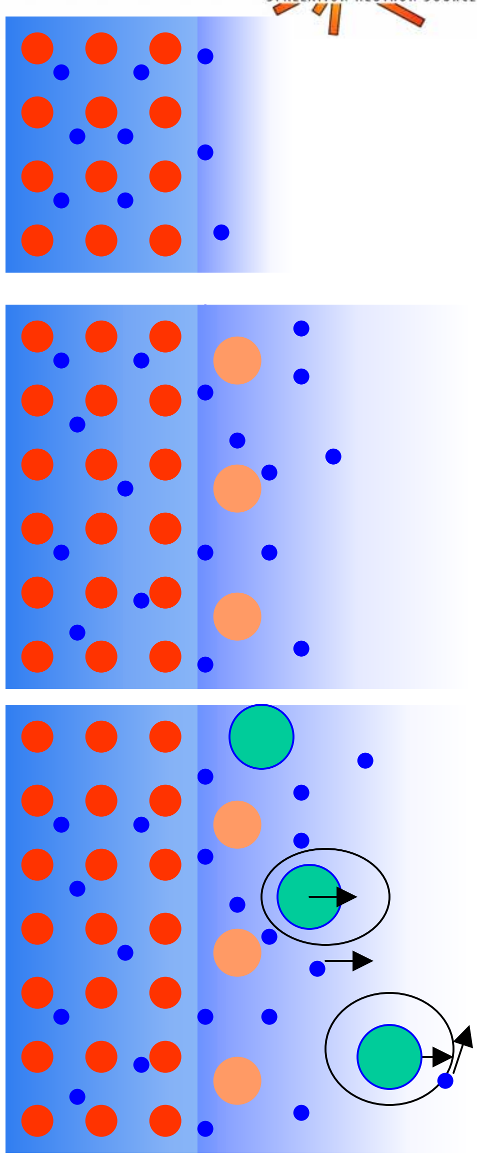


- The Cesium ionization energy greatly differs from the 0.75 eV electron affinity of H^-, and therefore H atoms **cannot** easily capture the outer electron from Cs.

So how can Cs be used for H^-?

Surface Production of Negative Ions

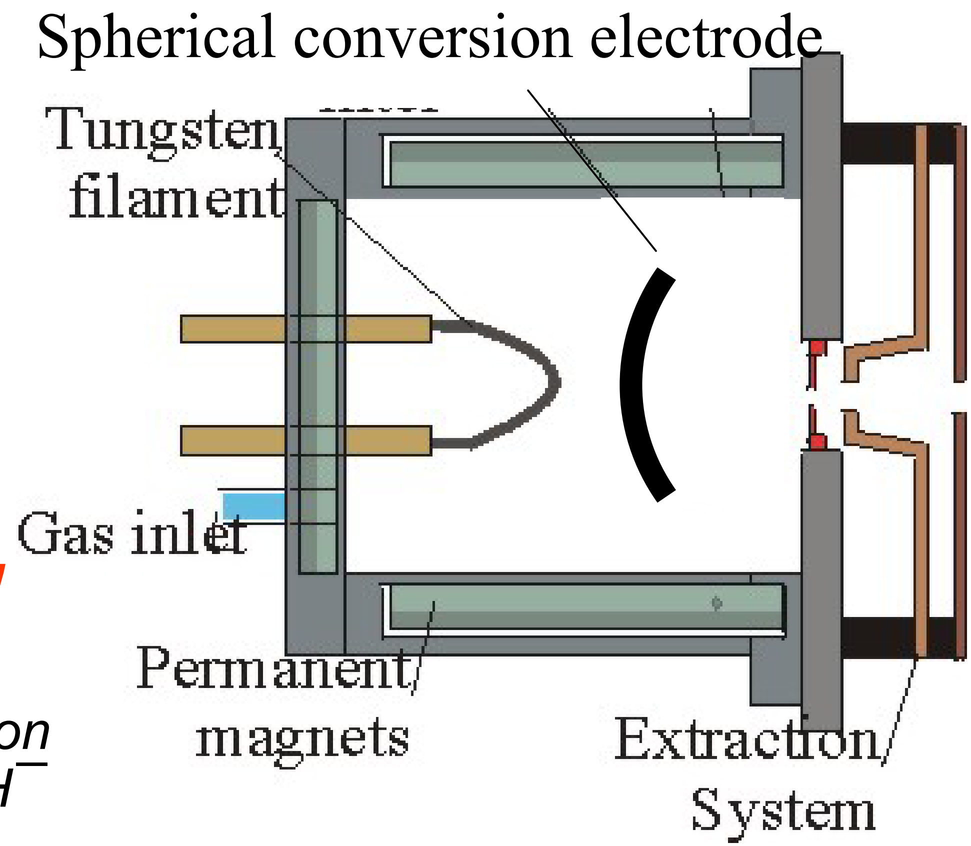
- *Metals host an abundance of loosely bound electrons (conduction electrons) but it takes about 4.5 to 6 eV to remove an electron from the surface (called work function).*
- *Cesium, a liquid metal at room temperature, has a work function of 2 eV only. But when condensed on a cold metal surface, Cs can lower the surface work function even further to 1.4 to 1.8 eV when covering about 60% of the surface (0.6 mono-layers).*
- *Atoms with an electron affinity in excess of 2 eV can easily pick up an electron and form an negative ion when desorbing from the surface.*
- *An experiment points to H^- being formed mostly by desorbing H atoms. But this requires the H atoms to transfer about 1 eV energy to the electron while leaving the surface. Therefore theory suggests H^- being formed by fast ions reflecting from the surface.*



Who cares, we know it works very well !!

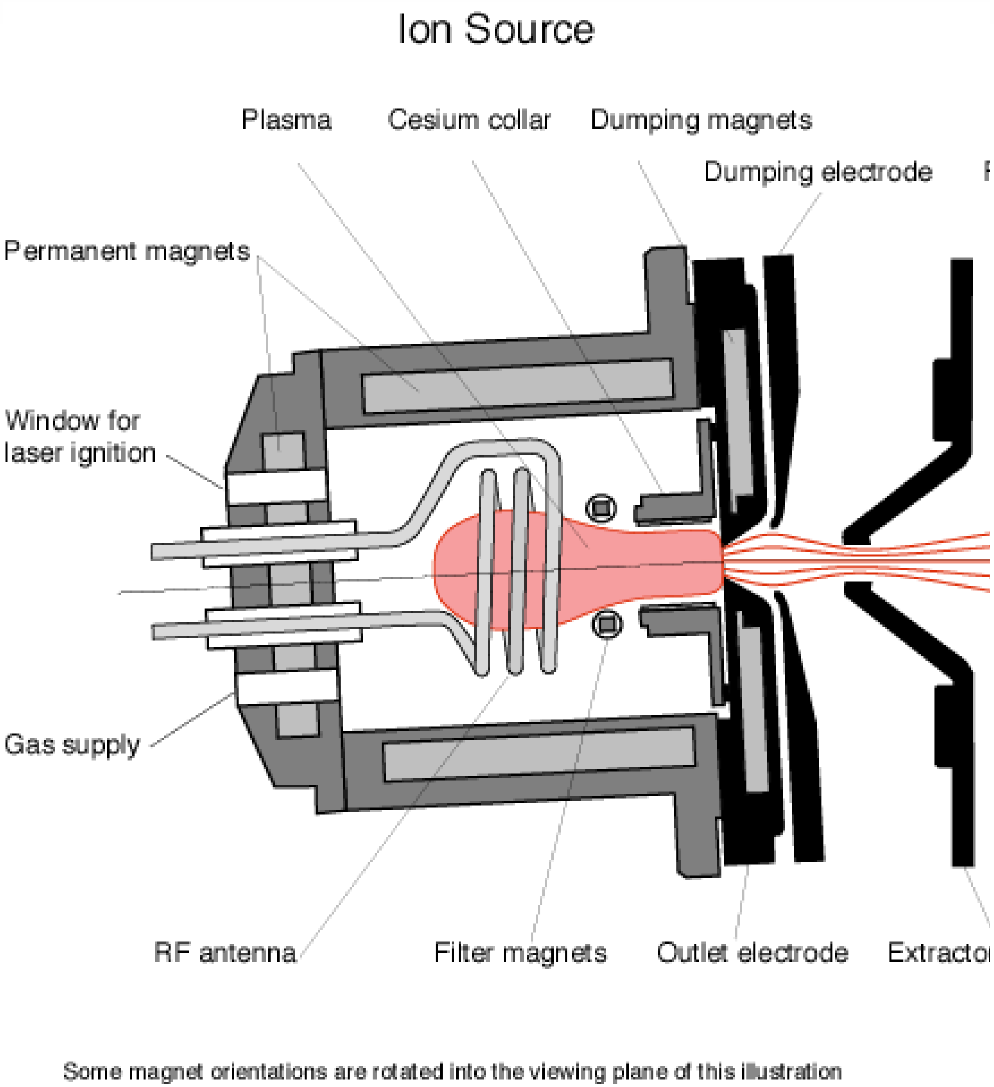
Surface converter ion source

- The experimental finding of the frequent emission of H^- from cesiated surfaces lead to the invention of the surface converter ion source. Being developed at LBNL three are now in operation in Los Alamos.
  - A filament driven plasma supplies ions and other particles to the surface conversion electrode. Location and orientation of filaments is critical !
- The voltage applied to the water cooled spherical surface conversion electrode accelerates desorbing H^- towards the extraction aperture.
- The surface conversion electrode needs to be kept well cesiated.



Filament lifetime limits ion source lifetime !

Free Electrons, the unavoidable problem



- Free electrons are needed for ionization, dissociation, and attachment.
- Free electrons have the same charge as negative ions and therefore the electric extraction field extracts the negative ions as well as an abundance of electrons. This electron current can dramatically exceed the negative ion current, resulting in a higher-power requirement for the high-voltage supply and in an X-ray hazard.
- A magnetic dipole field in the extraction aperture is typically used to minimize the extraction of electrons and/or to dump the escaping electrons before they gain too much energy, on the SNS dumping electrode.
- This parasitic electron beam can be substantially reduced with Cs.

1999 High-Current H- sources

From J. Peters,

RSI 71, 2000, 1069

Institution	Current	Duty factor	emittance N,90%	Brightness	Source Type	Tested uninterrupted	consumption	Accelerator experience
Units	ma	%	Pi mm mrad	(mA/mm mrad)^2		run hours	Cs per day	years
DESY	60	0.05	0.98	6.4	magnetron	7224	2.8 mg	17
BNL	75	0.48	1.2	4.9	magnetron	4320		
RAL	35	2.5	0.3		Penning	960		16
BINP	80	2.5	0.1	670	Penning		24 mg	
LANL	16	12	0.53	5.8	converter with filaments	720	480 mg	
TRIUMF	20	100	0.75	3.6	volume with filaments	500	No Cs	
TRIUMF	20	100	0.52		volume with filaments		5 mg	10
Frankfurt U	120	6	~0.23		volume with filaments		29 mg	
LBNL	30	0.1	0.5	12	RF antenna in plasma	72-984	K	
LBNL	91	0.1	0.5	28	RF antenna in plasma		Cs	
DESY	40	0.05	0.	7.2	RF antenna in air	7000	No Cs	

Which ion source should be a back-up for SNS?

•After having the antenna problem solved, the RF driven multicusp ion source is expected to provide the required H^- currents with a high reliability and an exceedingly long lifetime. If, however, we encounter unexpected problems we could implement an:

•An RF driven multicusp ion source with an air antenna (DESY) although there is no experience at high duty cycle.

•Or a filament driven surface converter ion source (LANL) although high reliability experience is restricted to 16 mA, and source requires significant maintenance when replacing filaments.

•Or a Magnetron ion source for which lifetime is limited but there is plenty of accelerator experience exists (Seminar by Dudnikov, January 2002).

•Or a Penning source for which lifetime is limited but plenty of accelerator experience exists (Seminar by Sherman, spring 2002).

It's a DESY source, says Norbert.

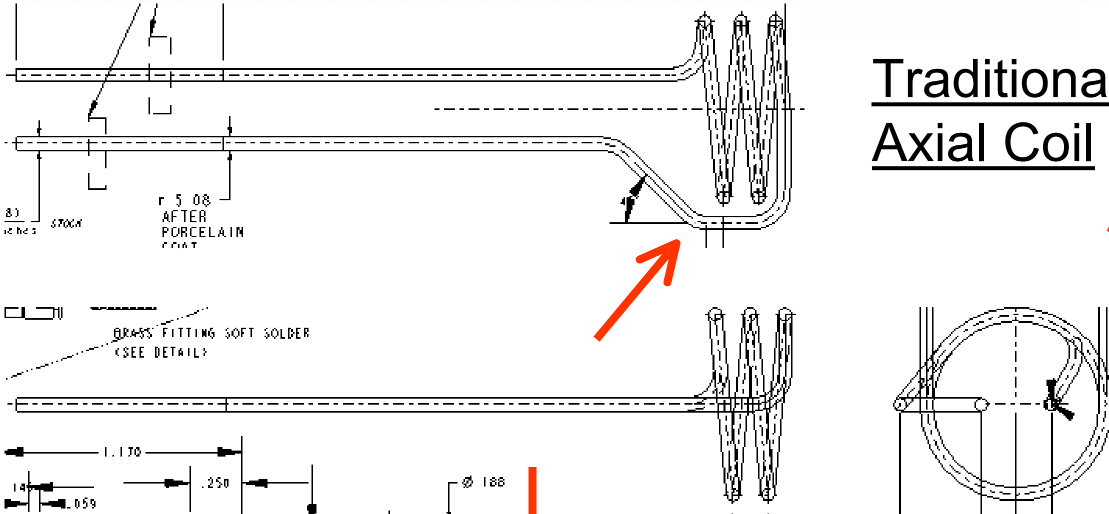
For Ion Source 102 please read:

Below are 10 titles sorted in bestselling order:

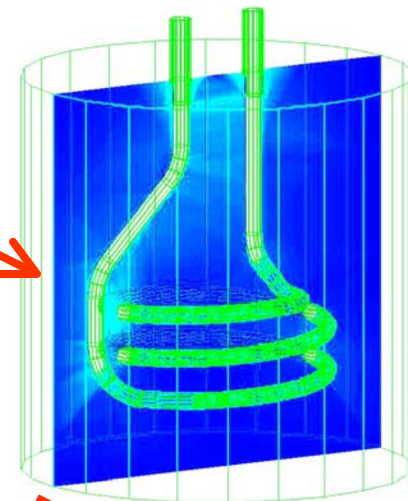
1. ***Ion Sources,*** *Huashun S. Zhang,Jianrong Zhang, Springer-Verlag, 2000, $119.00*
2. ***Electron Beam Ion Sources and Traps and Their Applications,*** *Krsto Prelec, Springer-Verlag, 2001*
3. ***Electron Cyclotron Resonance Ion Sources,*** *R. Geller, IOP Pub, 1996, $210.00*
4. ***Focused Ion Beams from Liquid Metal Ion Sources,*** *P. D. Prewett,G. L. Mair, Wiley, 1991*
5. ***Handbook of Ion Sources,*** *Bernhard H. Wolf, CRC Press, 1995, $194.95*
6. ***International Symposium on Electron Ion Beam Sources and Their Applications,*** *Ady Hershcovitch, American Institute of Physics, 1989, $85.00*
7. ***Physics and Technology of Ion Sources,*** *Ian G. Brown, Wiley, 1989.*
8. ***Polarized Ion Sources and Polarized Gas Targets,*** *L. W. Anderson, American Institute of Physics, 1994, $288.00*
9. ***Polarized Proton Ion Sources,*** *G. Roy & P. Schmor, American Institute of Physics, 1983, $37.00*
10. ***Polarized Proton Ion Sources,*** *Alan D. Krisch & A. M. Lin, American Institute of Physics,1981, $30.00*

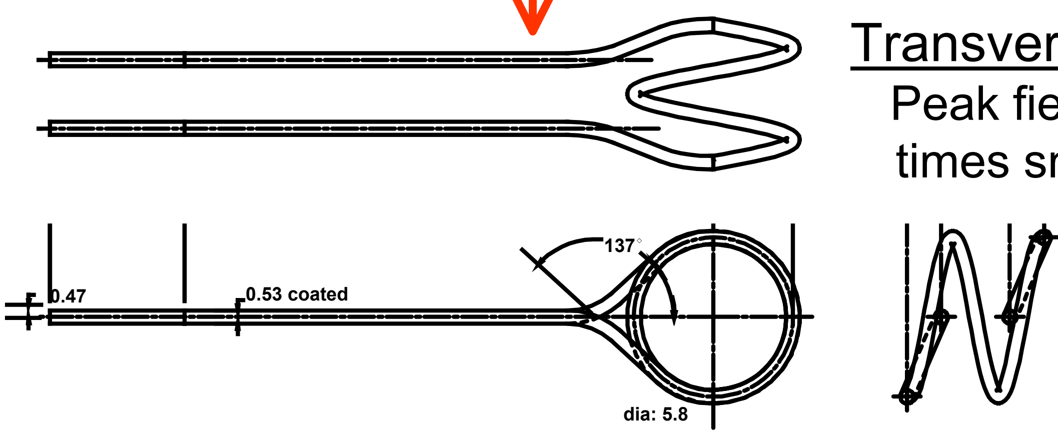
From http://shop.barnesandnoble.com

Can lifetime be extended with “improved” antenna geometry?



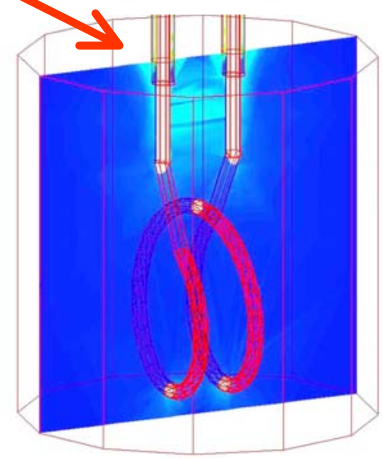
Traditional Axial Coil





Transverse Coil

Peak field 2-3 times smaller



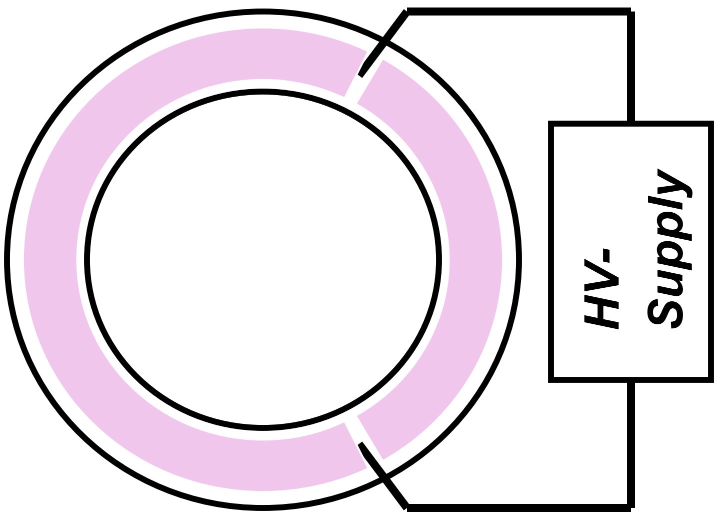
Peak Electric Fields calculated with HFSS by Y. Kang

The antenna geometry can be changed to increase the distance between parts with the highest voltage difference to reduce the peak electric field.

Will the reduced peak electric field increase the lifetime ?

Paschen Experiment

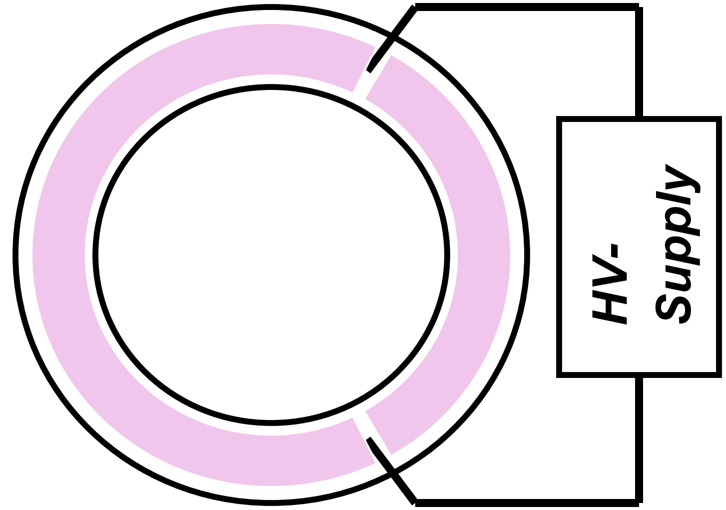
•Glass toroid filled with 0.1 Torr H_2. Electrodes form a 125 mm and a 250 mm gap. Apply voltage 290V, 300V,……390V, 400V

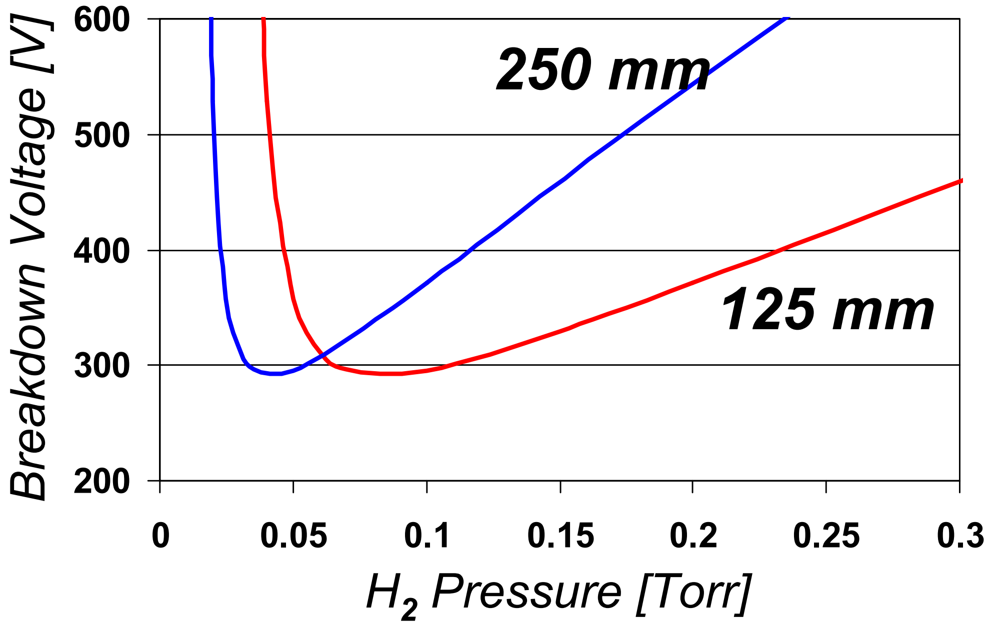


Paschen Follies

•Glass toroid filled with 0.1 Torr H_2. Electrodes form a 125 mm and a 250 mm gap. Apply voltage 290V, 300V,……390V, 400V

•Now reduce pressure to 0.05 Torr. Apply voltage …. 290V, 300V, …….390V, 400V





At pressures below the Paschen minimum discharges between more distant electrodes are more likely because they benefit from a higher electron multiplicity!!!

Credits due:

This work presented contributions from:

- Mark Janney and Bob Lauf, Metal & Ceramics Division, ORNL, USA
- Rainer Thomae, Thomas Schenkel, Rod Keller, Rick Gough, Jani Reijonen, Sami Hahto, Ka-Ngo Leung, LBNL, USA

- and most importantly the SNS ion source group in Oak Ridge:
  Robert Welton, Paul Gibson and Syd Murray

Thank you for your attention !